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Division of Building Research, National Research Council Canada

CBD 28

Wind on Buildings

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*W. A. Dalgliesh and D. W. Boyd**

Please note

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In the past very simple concepts have frequently been used in estimating live loads for structural design. Now, however, live loads on buildings, such as wind, snow, earthquake and floor loads, are receiving increased attention to match the more accurate structural analyses that are possible.

Wind loads have become particularly significant because of the increasing number of high-rise buildings. Other factors have also contributed to the importance of wind in design: light-weight low-slope roofs, curtain wall construction and the appearance of special structures having "aerodynamic shapes."

Some tall buildings that extend into regions of high wind velocity have swayed excessively in strong winds. Improperly anchored light-weight roofs have been sucked off bodily by wind forces, and roofing materials have been lifted by high local suctions and eventually peeled from large areas of roofs. These and many other problems have emphasized the importance of a clearer understanding of wind and its effects.

With the old simplified approach, the total effect of wind was often represented merely by a uniform lateral pressure on the windward side of a building and a suction on the leeward wall. Crossly simplified rules were also used to calculate pressures or suctions on roofs. Only the horizontal shear and overturning moment were calculated. For low or medium height buildings, such simple methods may have been reasonably satisfactory, but for tall buildings the greater importance of wind loading calls for more accuracy.

Wind is not constant either with height or with time, is not uniform over the side of a building, and does not always cause positive pressure. In fact, wind is a very complicated phenomenon; it is air in turbulent flow, which means that the motion of individual air particles is so erratic that in studying wind one ought to be concerned with statistical distributions of speeds and directions rather than with simple averages or fixed physical quantities.

Architects and engineers are concerned with and responsible for not only structural design, but also the choice of exterior cladding materials and components, the operation of mechanical services such as heating and ventilating equipment, and with details of openings to limit infiltration. Wind has important effects on each of these aspects of design; one might even conclude that of A the manifestations of nature with which the architect has to contend, apart from gravity, the effects of wind are the most ubiquitous.

It is the intent of this Digest to describe briefly the cause and structure of wind, and to explain how its structure complicates the determination of a reasonable design wind speed. The detailed discussion of the interactions between wind and buildings, and the actual pressures and suctions on parts of buildings are beyond the scope of this note.

Development of Wind

Wind usually refers to the movement of air parallel to the earth's surface. In this Digest we are concerned only with winds in the lowest few hundred feet of the atmosphere. The driving forces for such movements are pressure differences caused by unequal heating of the air. For a steady wind, however, the direction of flow does not follow the steepest pressure gradient from a "high" to, a low" as one might expect. In fact, the direction of flow is more nearly parallel to the isobars (lines connecting points of equal pressure) rather than perpendicular to them. This is because every object moving across the earth's surface is deflected to the right in the northern hemisphere (to the left in the southern) as a result of the rotation of the earth. This deviating effect, called the Coriolis force, is small and is usually disregarded except in the atmosphere and the ocean. The pressure gradient causing wind, however, is also small. Normally, wind requires several hours to develop, and although flow begins perpendicular to the isobars, it is gradually deflected to the right as time passes, so that when a steady state is finally attained the wind blows more nearly parallel to the isobars. The pressure gradient is then balanced by the Coriolis force and the frictional drag force, plus or minus centrifugal force if the path happens to be curved.

Velocity Profile

The roughness of the earth's surface, which causes drag on the wind, converts some of the wind's energy into mechanical turbulence. Since the turbulence is generated at the surface, the surface wind speed is much less than the wind speed at higher levels. Turbulence includes vertical as well as horizontal air movement and hence the effect of the surface frictional drag is propagated upwards. The mechanical turbulence and the effect of frictional drag gradually decrease with height and at the "gradient" level (around 1000 to 2000 feet) the frictional effect is negligible. The pressure gradient at this level is balanced by the Coriolis force (and possibly the centrifugal force), and the wind blows almost parallel to the isobars.

For strong winds the shape of the vertical profile of the wind speed depends mainly on the degree of roughness of the surface, by which is meant the over-all drag effect of buildings, trees and any other projections that impede the flow of wind at the surface. Three typical velocity profiles are shown in Fig. 1, where the effect of variable surface roughness on the mean wind speeds is shown for an arbitrarily selected gradient wind of 100 mph.

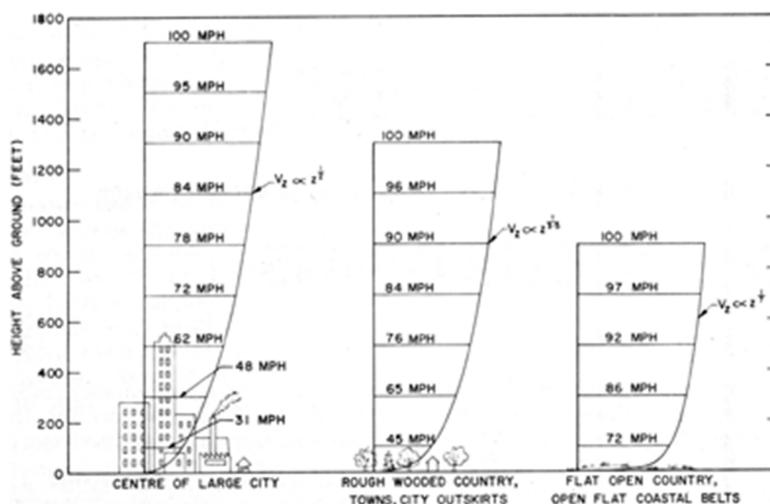


Figure 1. Mean velocity profiles over terrain with three different roughness characteristics for gradient wind of 100 mph

Velocity profiles have been determined by fitting curves to observed wind speeds at several levels. It is convenient and sufficiently accurate to describe these profiles by a power law of the form

$$V_h = V_r \left(\frac{h}{h_r} \right)^k$$

where V_h is the mean wind speed at height h above the ground,
 V_r is the mean speed at the reference height h_r , above the ground,
 k is the exponent for the best-fitting curve.

Courtesy Meteorological Division, Department of Transport

A reference height of 10 metres or about 30 feet is internationally recommended as the standard, and anemometers are usually mounted as close to this height as is practical. Exponents for mean wind speeds vary from about 1/7 for flat open country to about 1/2 for the centres of large cities.

Turbulence in Surface Winds

The velocity profile describes only one aspect of the wind at the lower levels. Superimposed on the mean speed are gusts and lulls, which are deviations above and below the mean. These gusts have a random distribution over a wide range of frequencies and amplitudes, both in time and space. Figure 2 shows clearly the unsteady nature of wind speed measured by an anemometer. Gusts are frequently the result of the introduction of fast moving parcels of air from higher levels into slower moving strata of air. This mixing or turbulence is produced by surface roughness and thermal instability.

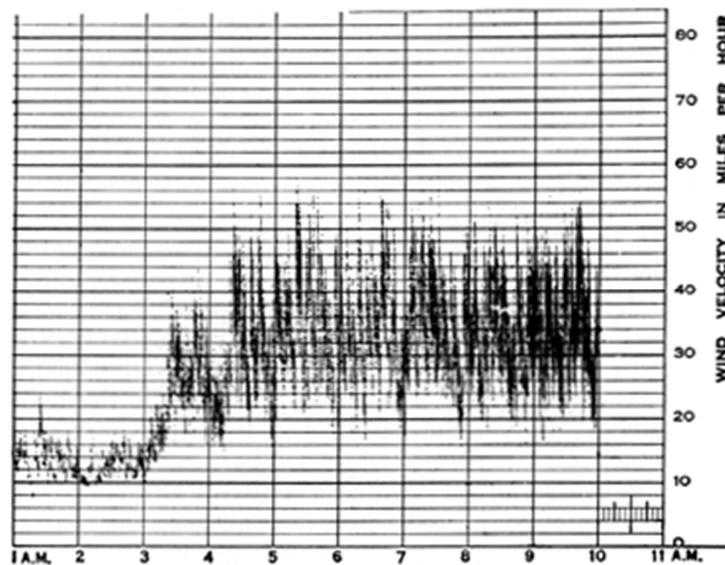


Figure 2. Typical pressure tube anemometer record

Turbulence caused by surface roughness is similar to the turbulent boundary layer flow at the walls of pipes. Flow near the surface encounters small obstacles that change the wind speed and introduce random vertical and horizontal velocity components at right angles to the main direction of flow. Turbulence generated by obstacles may persist downwind from projections as much as 100 times their height.

Large scale topographical features are not included in the above-mentioned surface roughness. They influence the flow, however, and should be given special consideration in design. For instance, wind is usually much stronger over the brow of a hill or ridge because the flow lines

converge over the obstructing feature and to pass the same quantity of air a higher speed is required. Large valleys often have a strong funnelling effect that increases the wind speed along the axis of the valley.

The thermal stability of air has a considerable effect on the intensity of turbulence. Cold surface air tends to damp out mechanical turbulence; heated surface air tends to rise and to increase turbulence. When the wind is strong, the air near the surface becomes thoroughly mixed and the thermal stability becomes neutral. Under these conditions temperature differences are such that they neither damp out nor increase the mechanical turbulence caused by surface roughness.

Design Wind Speeds

The basic design wind load in the National Building Code of Canada is the velocity pressure of a wind lasting for a few seconds that will be exceeded on the average once in 30 years. About twelve stations in Canada have pressure tube anemometers that record such gust speeds, but no records are available going back much more than 10 years. The only wind records covering many stations and many years are of the number of miles of wind passing the revolving cup anemometer each hour. The annual maxima of these hourly mileages or hourly mean wind speeds have been analysed to yield the hourly mileage that will be exceeded on the average once in 30 years. Peak gusts at the few stations where they are recorded have been compared with corresponding hourly mileages, and the resulting relationship has been used to estimate peak gusts at other stations.

Figure 1 indicates that average wind speeds at low levels in cities are much less than those in open country. The gustiness of city winds is greater, however, and peak gusts in a city may not be much less than peak gusts at a nearby airport. It is therefore somewhat conservative but reasonable to use measured or estimated peak gust speeds at an airport as the design wind speed for buildings up to about 40 feet high in a city or town.

Gust speeds at higher levels are stronger than those near the surface. Because gustiness decreases with height, however, increase in the speed of peak gusts with height will be less than the increase in mean wind speeds. For flat open country the exponent for gust speeds is probably about 1/10. For average conditions in Canada the more conservative exponent of 1/7 is commonly used.

Dynamic Effects

Every structure has a natural frequency of vibration, and should dynamic loading occur at or near it, structural damage out of all proportion to the size of the load may result. For example, bridges capable of carrying far greater loads than the weight of a company of soldiers have been known to break down under the dynamic loading of men marching over them in step.

Similarly, certain periodic gusts within the wide spectrum of gustiness in the wind may find resonance with the natural vibration frequency of a building, and although the total force caused by that particular gust frequency will be much less than the static design load for the building, dangerous oscillations may be set up. This applies not only to the structure as a whole, but also to components such as curtain wall panels and sheets of glass.

A second dynamic effect is caused by the instability of flow around certain structures. Long narrow structures such as smoke stacks, light standards and suspension bridges are particularly susceptible to this sort of loading. In such cases dynamic instability of flow may result when eddies separate first from one side and then from the other side of the object, causing an alternating pattern of eddies to form in its wake. A side thrust is thus exerted on the object similar to the lift on an aerofoil, and since this thrust alternates in direction a vibration may result. The side-to-side wobbling of a straight stick being pulled through water is an example of this phenomenon. Another example is the "galloping" transmission line extensively investigated by electric power companies.

Perhaps the most dramatic example of susceptibility to dynamic instability of flow was the failure of the Tacoma Narrows suspension bridge. Very moderate winds caused oscillations of up to 50 inches or more in amplitude, whereas very strong winds had little effect. When failure of the 2800-foot central span did occur in November 1940, the highest wind speed was only 42 mph, preceded by 2 hours of steady wind at 38 mph.

Conclusion

Some of the features of wind near the surface of the earth have been briefly described in this Digest. Particular attention has been given to gustiness and to the rates of increase of both mean wind speeds and peak gust speeds with increases in height. A method of computing design wind speeds from wind observations available in Canada has been outlined. These speeds form the necessary basis for the conversion of wind speeds into wind loads for various shapes of structures.

As research gradually provides a better understanding of the structure of wind and the complex interactions between wind and buildings, one can look forward to greater economy in the use of building materials through greater precision in estimating static load; and to greater safety as a result of the inclusion of the dynamic load in design.

* D. W. Boyd is a member of the staff of the Meteorological Division of the Department of Transport seconded to work full time as Climatologist with the Division of Building Research. This Digest therefore represents a joint contribution from this Division and from the Meteorological Division.